Shipboard Power Systems: Characteristics and Research Directions

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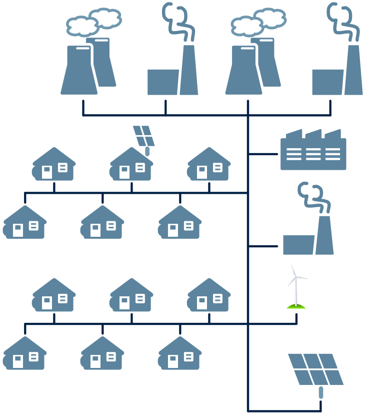
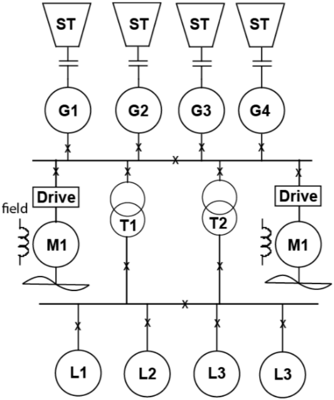
Basic Power System

Electric Utility



Shipboard[1]



[1] Jayasinghe et al., "Review of Ship Microgrids: System Architectures, Storage Technologies and Power Quality Aspects," *Inventions*, vol. 2, no. 4, February 2017.

Typical Shipboard Loads

- Propulsion motor: induction, synchronous, permanent magnet, etc.

Future direction: high phase-count motor drives[2]

✓ Lower per-phase current

✓ Lower loss and cost

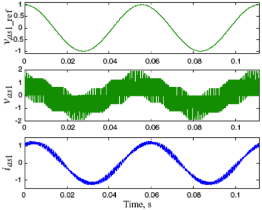
✓ Higher reliability

Greater chance of completing mission

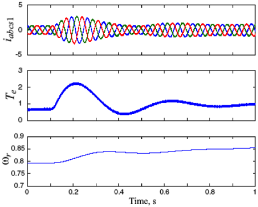
Why is this difficult?

✗ Designs are not mature

✗ Existing industry tools are not sufficient



Steady state stator voltage and current for the phase *as*1.



Induction motor response to the frequency and voltage increase.

[2] J. Jatskevich and M. Maksimcev, "Dynamic Modelling of 15-Phase 20 MW Baseline Induction Motor Drive for Electric Ship Propulsion," WSEAS Transactions on Systems, iss. 8, vol. 5, pp. 1785-1791, August 2006.

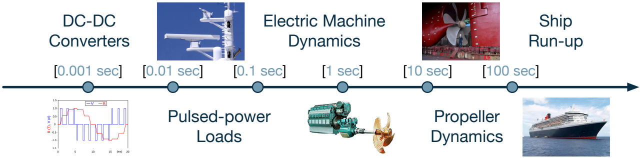
Typical Shipboard Loads

- Propulsion motor: induction, synchronous, permanent magnet, etc.
- Heating and cooling: pumps, compressors, etc.
- Pulsed equipment:
  - Electromagnetic weapons, high energy detection systems, etc.



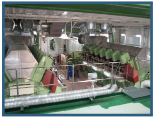

Main Challenges:

- Large changes in short time
- Wide range of time scales



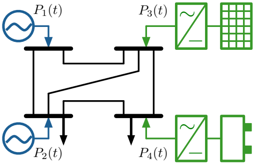
Typical Power Sources

- Turbine-based technologies
  - Steam turbine, diesel engine, gas turbine, combined cycle, etc.
- Fuel source
  - Coal, marine diesel oil, natural gas, nuclear, etc.



Future Directions: reduce environmental impact

- Renewable resources: solar and wind
- Energy storage systems: require less power



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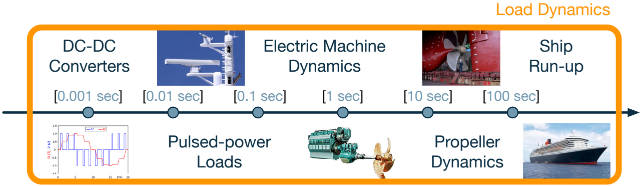

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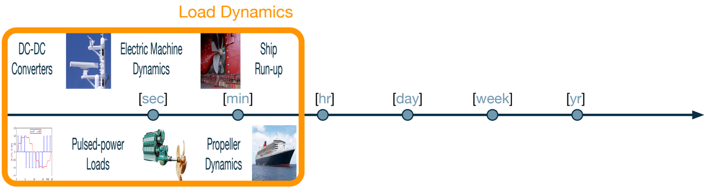

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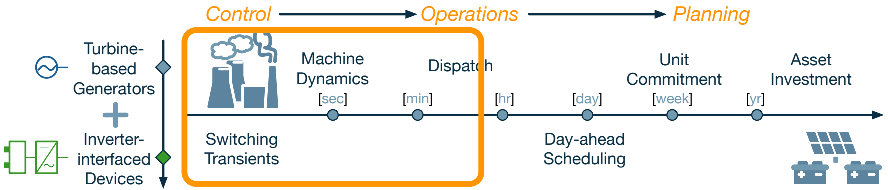
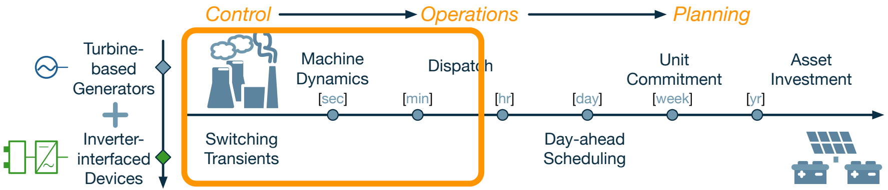


- Stability and Control
- Operations and Energy Management
- Planning and Asset Management

Taken Together



- Stability and Control
  - Low level of rotational inertia
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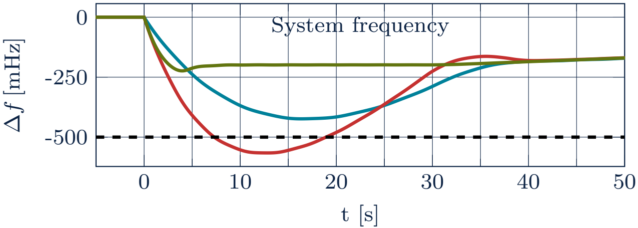
Effect of System Inertia on Frequency Dynamics[3]

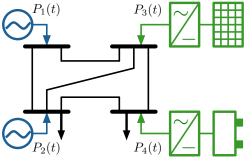


- High inertia ($H = 6\,\text{s}$), i.e., no wind & PV; nominal frequency control reserves
- Low inertia ($H = 3\,\text{s}$), i.e., 50% wind & PV; nominal frequency control reserves
- Low inertia ($H = 3\,\text{s}$), i.e., 50% wind & PV; fast control reserves

[3] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of low rotational inertia on power system stability and operation," *IFAC Proceedings*, 2014.

Advanced Control Example[4]

- Power-electronic converter controller emulates synchronous generator



[4] S. Dong and Y. C. Chen, "Adjusting synchronverter dynamic response speed via damping correction loop," *IEEE Transactions on Energy Conversion*, vol. 32, no. 2, pp. 608-619, June 2017.

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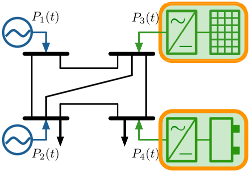

Main idea:

1. Abstract away internal dynamics

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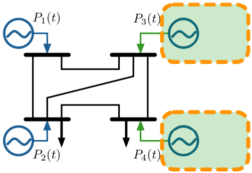

Main idea:

1. Abstract away internal dynamics
2. Embed generator model into controller

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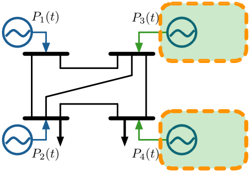

Main idea:

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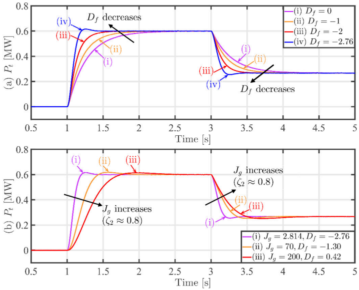
2. Embed generator model into controller

Why is this a good option?

✓ Regulates power output
✓ Provides frequency support
✓ Ensures system stability



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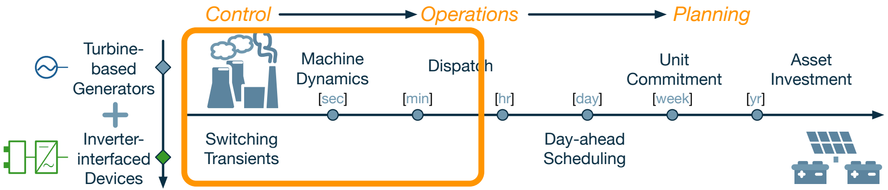


- Stability and Control
  - Low level of rotational inertia
  - Power quality (e.g., voltage dips, harmonics, etc.)
- Operations and Energy Management
- Planning and Asset Management

Power Quality Issues—Halifax-class Frigates[5]

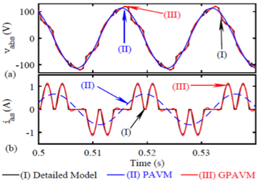
- Many new nonlinear rectifier loads
  - Motor drives, converter loads, etc.
- High-frequency electronic loads
  - Example: connection to helicopter

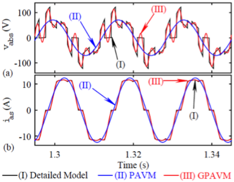
Why is this a problem?

✗ Complex interactions

✗ Possible incompatibilities

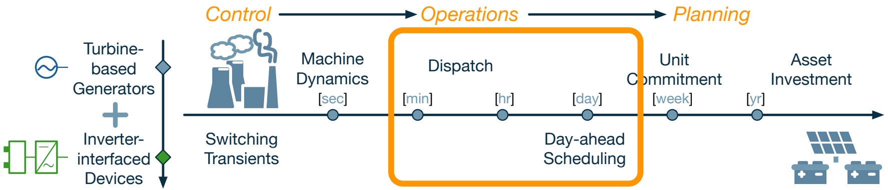
✗ Leads to harmonics and poor power quality





[5] J. Jatskevich and S. Ebrahimi, "Halifax Class Power Distribution Harmonic Study—Report and Simulation Results," Report to Department of National Defence (DND), Canada, Quality Engineering Test Establishment, April 2018.

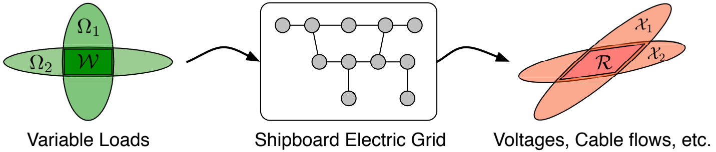
Taken Together



- Stability and Control
  - Low level of rotational inertia
  - Power quality (e.g., voltage dips, harmonics, etc.)
- Operations and Energy Management
  - Wide range of time scales
  - Uncertainty in loads
- Planning and Asset Management

The Reachability Problem

- Determine effect of uncertain loads on grid performance[6]

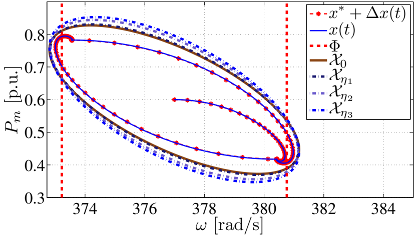


Why is this useful?

✓ Guaranteed worst-case deviations of system states for bounded inputs

✓ Amenable to computer simulation

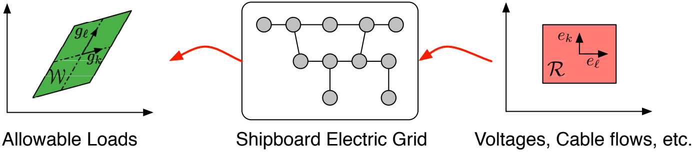
✓ Computationally tractable



[6] X. Jiang, Y. C. Chen, and A. D. Domínguez-García, "A set-theoretic framework to assess the impact of variable generation on the power flow," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 855-867, May 2013.

The Inverse Problem

- Determine feasible loads subject to operational constraints[7]

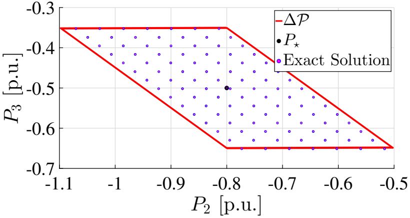


Why is this difficult?

✗ Nonlinear system

✗ No closed-form solutions

✗ Linearization at the expense of accuracy



[7] A. Al-Digs, S. V. Dhople, and Y. C. Chen, "Estimating feasible nodal power injections in distribution networks," in *Proc. of IEEE PES Innovative Smart Grid Technologies Conference*, Minneapolis, MN, September 2016.

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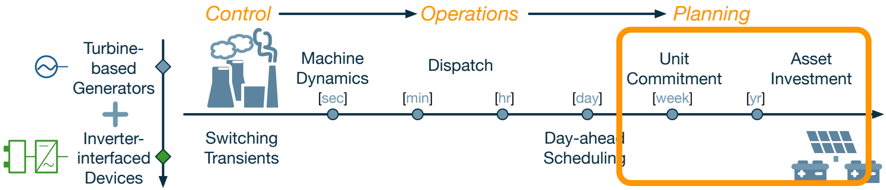

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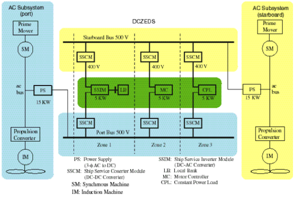
  - Low level of rotational inertia
  - Power quality (e.g., voltage dips, harmonics, etc.)
- Operations and Energy Management
  - Wide range of time scales
  - Uncertainty in loads
- Planning and Asset Management
  - Interdependencies, reliability, and resilience
  - Shipboard architectures (e.g., AC vs. DC, radial vs. zonal, etc.)

Futuristic Example–Zumwalt-class Destroyer

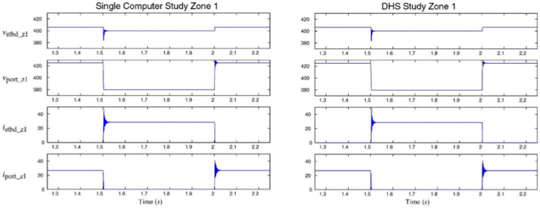
- Integrated power system[8]
- DC zonal electric distribution system
- Greater efficiency, reconfigurability, and survivability

Modelling, simulation, and analysis are absolutely necessary!



DHS Implementation:
5 models distributed across 3 computers

Computer 1 Computer 2 Computer 3



[8] C. E. Lucas, E. A. Walters, J. Jatskevich, "Distributed Heterogeneous Simulation of Naval Integrated Power System," American Society of Naval Engineers, Electric Machine Technology Symposium, Philadelphia, PA, January, 2004.

Electric Power and Energy Systems Group at UBC

✓ World-renowned in modelling, simulation, and analysis of power systems, power-electronic devices, and electric machines

✓ Expertise directly applicable to shipboard power systems

1. Design future Canadian ships
   - Development, prototype, and verification of models and algorithms
   - ✓ Fine-tune critical design decisions prior to real-world implementation
2. Retrofit and modernize existing ships
   - Verification in simulation test bed prior to hardware realization
   - ✓ Avoid potentially lengthy and costly delays
3. Train next-generation marine engineers
   - Partner with marine industry so students obtain real-world experience
   - ✓ Prepare engineers to fulfill Canadian naval architecture needs